Nonlinear Internal Tide Generation at the Luzon Strait: Integrating Laboratory Data with Numerics and Observations

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LONG-TERM GOALS

Ongoing advances in laboratory experimental techniques have greatly enhanced the ability to obtained detailed spatiotemporal data for internal waves in challenging regimes. The long-term goal of this research is to use the latest experimental techniques to investigate internal wave dynamics relevant to the Luzon Strait in a custom configured wave tank; and to integrate these results with data obtained from numerical simulations, theory and field studies. The principal focus is to determine the generation mechanism for large amplitude solitary waves originating from the Luzon Strait, which is presently undetermined.

OBJECTIVES

While there is currently a good predictive capability for the timing of internal waves generated at the Luzon Strait, there is no reliable ability to predict their amplitude. This is evidenced by the recent (Aug 08) NLIWI cruise, for which the internal waves were much smaller in amplitude than anticipated. It is clear that developing a predictive capability for this aspect of the waves will require a more detailed understanding of the generation mechanism, accounting for stratification and tidal forcing, which vary. The objectives of this project are: to establish good agreement between experiments, theory and numerical simulation for the generation of internal waves in a variety of regimes; to investigate the impact of different governing parameters on internal wave generation; and to then identify the particular scenario relevant to Luzon. For confirmation, the experimental data should explain available field data.

APPROACH

The approach revolves around a custom designed wave tank that was constructed, installed and tested over the last two years. Important features of the wave tank include: a computer controlled filling mechanism that enables the establishment of nonlinear density stratifications, rapid prototyping of topography using a foam cutter, computer controlled topographic motion for complex tides, and sophisticated visualization equipment for measuring velocity fields, density fields and density gradient fields.

WORK COMPLETED

We have continued our program of investigating internal wave generation by topography in the wave tank, making direct comparisons of our experimental results with predictions of numerical simulations by Kraig Winters and Jim McWilliams. These studies have obtained the first measurements of modal decomposition and energy-flux of internal tides from experimental data sets. We have also completed a combined experimental and theoretical study of how wave beams, which may be generated by the Luzon ridges, interact with the thermocline, leading to internal wave trapping (ducting) and possibly the generation of solitary waves. Theoretical investigations on the existence of an internal wave attractor between ridges have clearly identified a region at the northern end of the Luzon Strait where this might be possible. To further support these ray tracing studies, we have developed an analytical model that uses a Green function approach to determine the linear tide radiated from a double ridge system. Most recently, we have designed and installed a new parabolic dividing wall in the experimental wave tank to facilitate future experiments.

From this work, there have been two submitted manuscripts (Echeverri et al. 2008, Mathur & Peacock 2008). Oral presentations have been given at Cornell University, University of Grenoble, Cambridge University, University of British Columbia and the Ocean Sciences meeting in Orlando. The PI has coordinated a session on Internal Waves at the upcoming AGU Fall meeting, as well as helping coordinate a recent NLIWI cruise in August 08 to provide material for a proposed Discovery Channel documentary on Internal Waves, in which the NLIWI program will be highlighted

RESULTS

(i) **Internal Tide Generation**

A detailed comparison between experiment, theory and numerics was pursued in collaboration with Kraig Winters. The goal of the experiments was to determine the effect of finite-amplitude excursion parameter on the radiated internal tide from an isolated topographic feature. Examples of the experimental, numerical and theoretical wave fields for sub and supercritical topography are presented in figure 1. Very good agreement was obtained between the three different methods, validating our collaborative approach. From the experimental data we obtained the first ever experimental measurements of energy flux and modal decomposition for internal tides. The modal decompositions are presented in figure 2, in which modal amplitudes and phases are plotted as a function of criticality. The most significant result we obtained was that as the excursion parameter was significantly increased for subcritical Froude numbers, while still remaining in the internal tide regime, the relative amplitude of mode-1 remained constant (despite the presence of highly-nonlinear behavior at the generation site). This result lends support to the belief that the generation mechanism at Luzon is likely a nonlinear steepening of the radiated mode-1 tide.
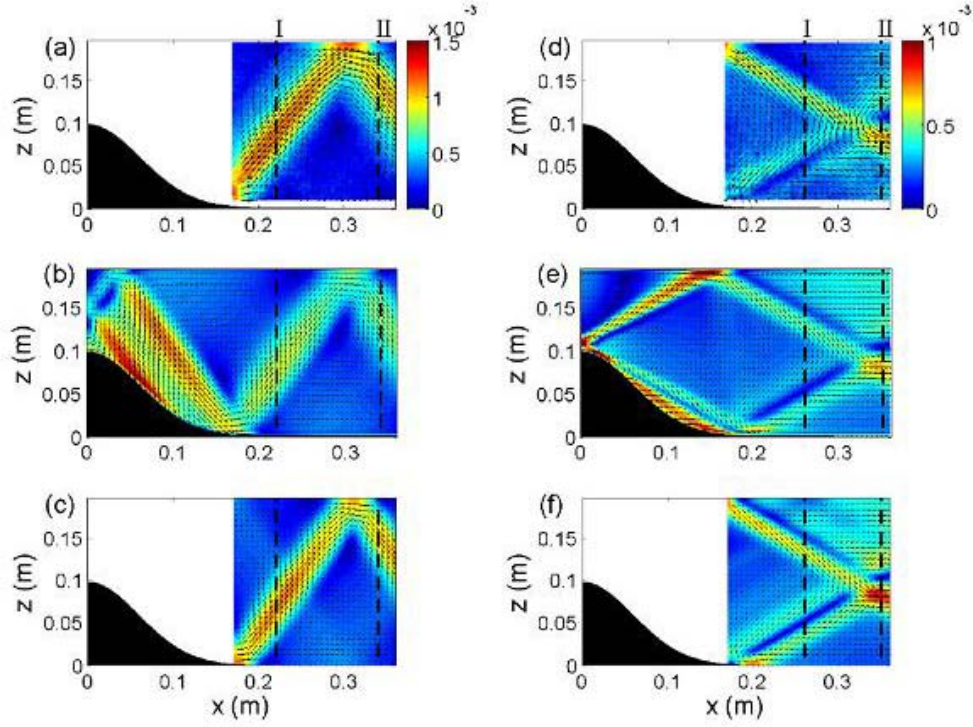
Figure 1: Experimental (top), numerical (middle) and theoretical (bottom) velocity fields generated by subcritical (left) and supercritical (right) topography.
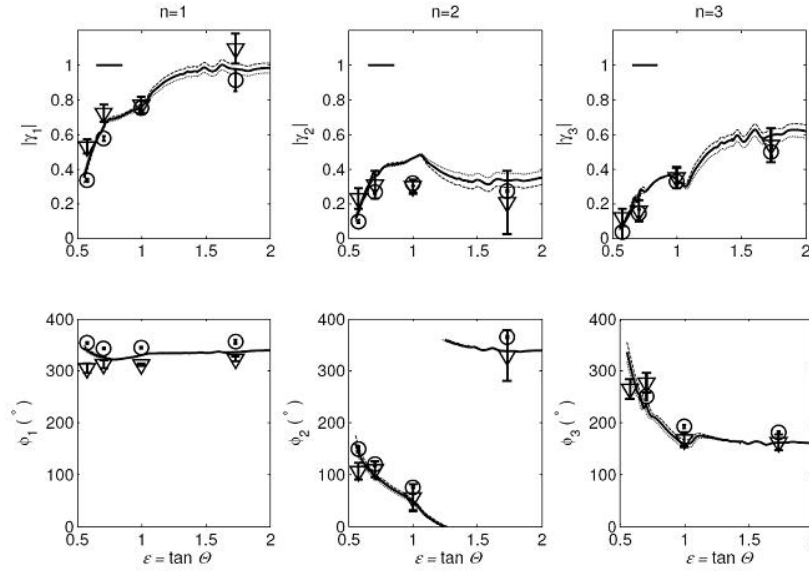

Figure 2: Modal decomposition of internal tides. The upper row presents amplitudes for modes 1, 2 and 3 and the lower row presents phase information, plotted as a function of criticality.

Further support for the idea that solitary waves in the South China Sea evolve from the nonlinear steepening of a low-mode tide comes from our continued comparisons with numerical simulations by the group of Jim McWilliams. For these experiments, all the dimensionless parameters at Luzon were reasonably reproduced in the wave tank, with the exception of the Reynolds number, which was $O(10^3)$. Overall, there was excellent agreement between experiment and numerics, as shown in figure 3. Having obtained this level of agreement, mutually confirming experiment and numerics, the Reynolds number was then raised in the numerical simulation. It was found that at higher Reynolds number, solitons emerge from a steepening of the mode-1 internal tide.
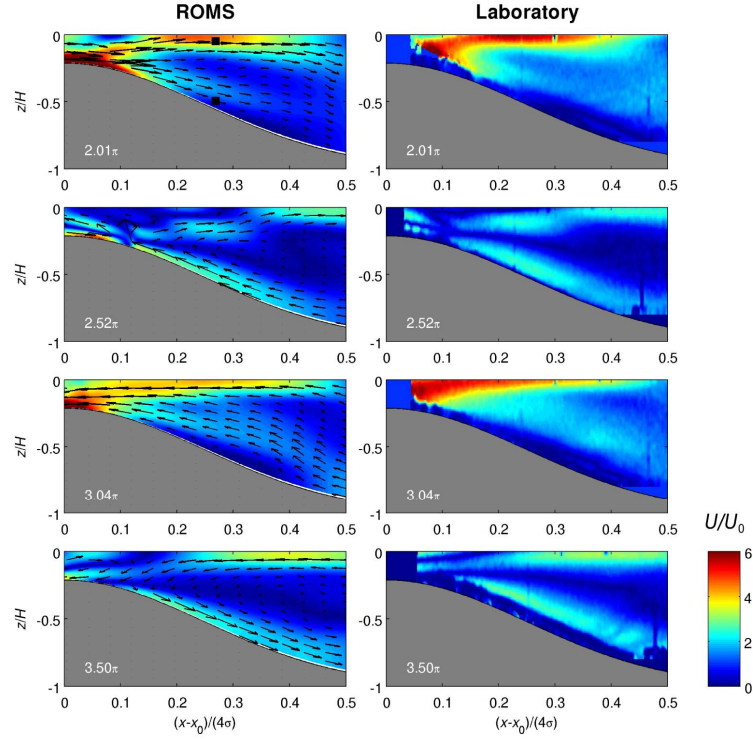

Figure 3: A comparison between laboratory experiments and the predictions of a ROMS simulation for a dimensionless parameter regime that matches the Luzon Strait.

(ii) **Internal Wave Beams**

It is quite possible that strong internal wave beams are generated at the Luzon ridge, in the same manner as many other geographical locations (Mathur & Peacock 2008). It is also known that the interaction of internal wave beams with the thermocline can produce solitary waves (Gerkema 2001). We have determined theoretically and demonstrated experimentally the best conditions for trapping internal wave beam energy in the vicinity of the thermocline. An example of wave beam ducting in a laboratory experiment is presented in figure 4. Based on our theoretical approach, we have identified that the conditions at Luzon are very well suited for ducting, and this should perhaps be taken into consideration in the planning of future field studies.
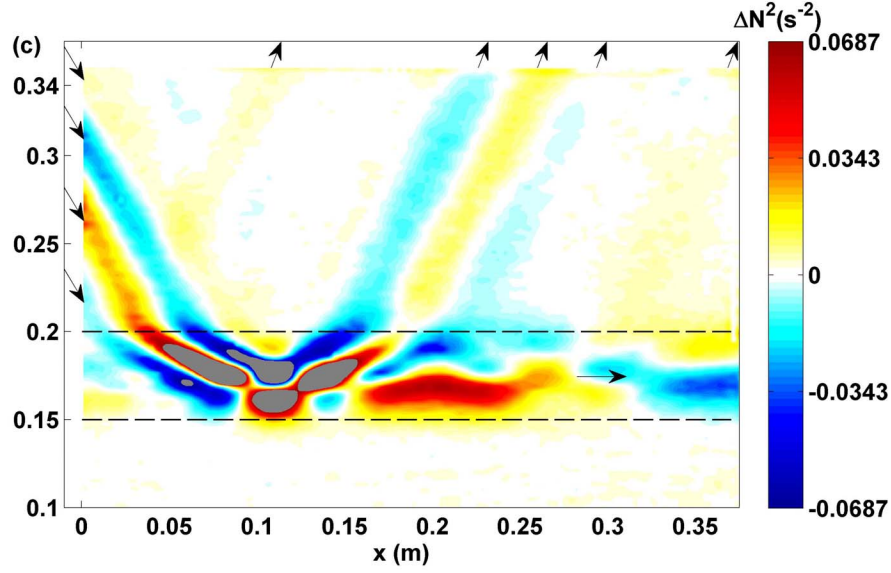
Figure 4: Ducting of an internal wave beam in a laboratory experiment, visualized using Synthetic Schlieren. An incident wave beam from the left hand side gets trapped within the thermocline.

(iii) **Internal Wave Attractors**

The Luzon Strait is unusual in possessing a double-ridge configuration. At this stage it is still unclear what role, if any, this plays in the generation of large amplitude solitary waves. One consequence of a double ridge is an ability to support internal wave attractors, i.e. closed ray paths onto which internal wave energy can be focused. This concentration of internal wave energy could be expected to promote instabilities and wave breaking. After an extensive survey of the ridge system, we have clearly identified the possible existence of an attractor at the northern end of the ridge, as shown in figure 5(left). In addition, to support these efforts, we are developing a Green function method for predicting the radiated internal tide from double ridges. We have already found that this arrangement can lead to large quantities of internal wave energy trapped between the ridges, as shown in figure 5(right). Perhaps even more significant would be the identification of asymmetry in the strength of the radiated internal tide for a ridge system in which the ridges were of significantly different height. This, in combination with stratification and tidal forcing, could play a role in explaining why there is asymmetry in the observations of solitons to the West and East of the Luzon Strait.
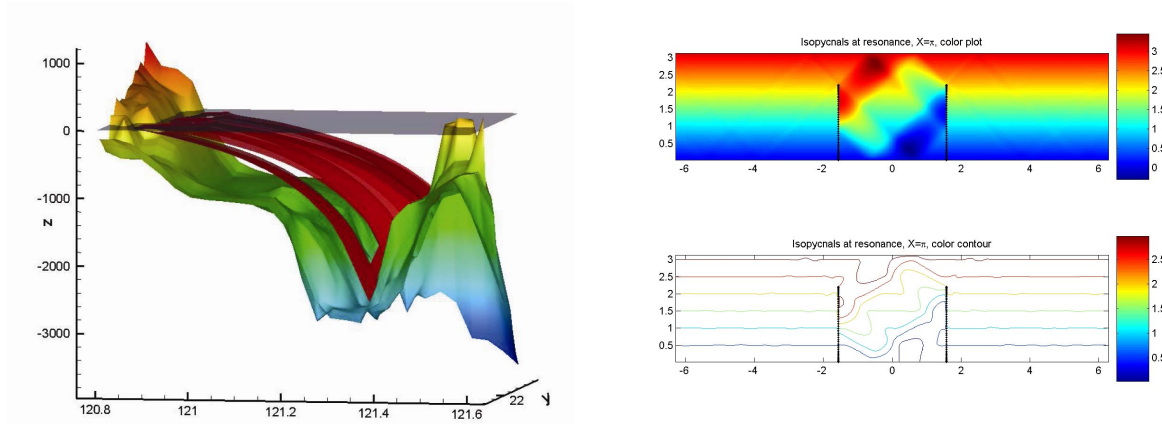
Figure 5: (left) An internal wave attractor at the northern end of the Luzon Strait. (right) Internal wave energy is concentrated between a pair of ridges.

IMPACT/APPLICATIONS

The results from the latest set of experiments support the belief that solitons propagating to the West of the Luzon Strait emerge from a nonlinear steepening of the low-mode internal tide. Our experimental results have also provided rigorous validation of two numerical models that are currently being used in the NLIWI investigations. Our identification of the existence of attractors in ray tracing models of the Luzon Strait and the development of a supporting theory for double ridge systems, plus our recognition of the possibility of internal wave ducting, may help guide future field studies at Luzon through the IWISE program.

RELATED PROJECTS

We are collaborating with Ren-Chieh Lien on investigations of internal wave attractors in the Luzon Strait. He has provided us with stratification data for our ray tracing studies, and in return is seeing whether he can identify an attractor in any field data sets. Having completed one project with Kraig Winters, we shall look to extend this collaboration, pursuing further interactions between our experiments and his numerics in regards to Luzon. We also intend to continue our collaboration with Jim McWilliams, with his group simulating the double-ridge geometries. Finally, once our analytical and experimental studies have established the parameter regimes for a double ridge geomtery, in the coming year we intend to run another experiment with dimensionless parameters matching those at Luzon, with the goal of comparing our results with field data obtained by David Farmer.

REFERENCES

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PUBLICATIONS

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